Proposal for all-electrical measurement of T_1 in semiconductors

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In an inhomogeneously doped magnetic semiconductor spin relaxation time T_1 can be determined by *all-electrical* measurements. Nonequilibrium spin injected in a magnetic *p-n* junction gives rise to the spin-voltaic effect where the nonequilibrium spin-induced charge current is very sensitive to T_1 and can flow even at no applied bias. It is proposed that T_1 can be determined by measuring the I-V characteristics in such a geometry. For a magnetic *p-n* junction where the results can be calculated analytically, it is in addition possible to extract the g-factor and the degree of injected carrier spin polarization.

In examining the properties of spin-polarized transport in solid state systems one of the key physical quantities is the characteristic spin relaxation time T_1 and the related length scale, spin diffusion length L_s, both describing the decay of nonequilibrium spin. These spin relaxation parameters play crucial roles in various novel spintronic applications [1]. Unlike in the conventional charge-based electronics, spintronic devices rely on manipulating nonequilibrium spin. Since T_1 and L_s determine "spin memory" they effectively set an upper limit on the time required to perform various device operations and the possible optimal size of spintronic devices. In semiconductor spintroncs [1], spin relaxation of carriers (electrons and holes) is a complex process [2,3]. For a given temperature and doping, several different mechanisms contribute to spin relaxation which is sensitive [2,3] to strain, dimensionality, magnetic and electric fields. It would be highly desirable if the same semiconductor structures which hold promise for spintronic applications could also be used to probe spin relaxation. Previous methods [2,3] to measure T_1 have typically used optical techniques or electron spin resonance.

In this letter we discuss a proposal to determine T_1 by *all-electrical* measurements from the I-V characteristics. This method can be viewed as a generalization of the concept of *spin-charge* coupling [4,5], introduced in metals by Silsbee and Johnson, to inhomogeneously doped semiconductors [6]. We show how several features, specific to semiconductors (bipolar transport–by both electrons and holes, bias-dependent depletion region, and highly nonlinear I-V characteristics), can be exploited to provide a sensitive probe for T_1.

To illustrate our proposal we consider a magnetic *p-n* junction [6,7] as sketched in Fig. 1a,b. In the p (n) region there is a uniform doping with N_a acceptors (N_d donors). Within the depletion region ($-d_p < x < d_n$) we assume that there is a spatially dependent spin splitting of the carrier bands. Such splitting, a consequence of doping with magnetic impurities, can occur in different situations. For example, in ferromagnetic semiconductors [8] or, in the presence of magnetic field B, the spin splitting could arise from either having inhomogeneous g-factors or by applying an inhomogeneous magnetic field. While

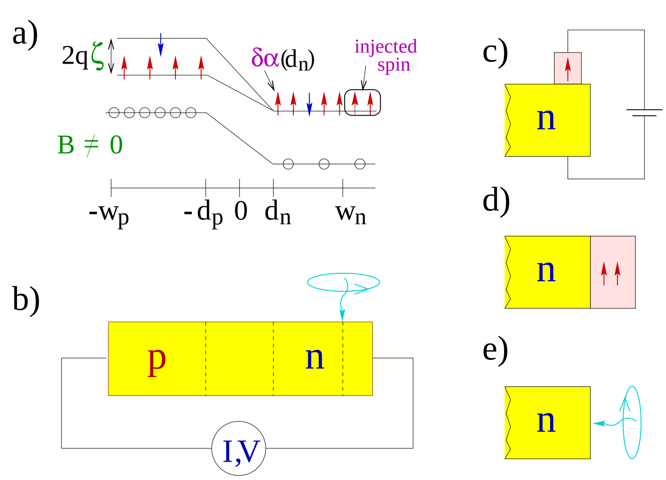

FIG. 1. Scheme of a magnetic *p-n* junction. a) Band-energy diagram with spin-polarized electrons (arrows) and unpolarized holes (circles). b) Circuit geometry corresponding to panel a). Using circularly polarized light, nonequilibrium spin is injected transversely in the nonmagnetic n region and the circuit loop for I-V characteristics is indicated. Panels c) - e) indicate alternative schemes to inject spin into the n region. Schemes c) and d) rely on the magnetic (paramagnetic or ferromagnetic) material to inject spin electrically. Realizations depicted in b), c), and e) are suitable to demonstrate spin-voltaic effect, where: 1) in a closed circuit charge current can flow, even at no applied (longitudinal) bias, with the direction which can be reversed either by $B \to -B$ or by the reversal of the orientation of the injected spin, 2) for an open circuit an analogous reversal in B or in the spin orientation would change the sign of the voltage drop across the junction.

our method is applicable to all of these cases, we focus here on the last two instances and further assume that the carriers obey the nondegenerate Boltzmann statistics. In the low injection regime it is possible to obtain the results for spin-polarized transport analytically and to decouple the contribution of electrons and holes [7]. Following the approach from Ref. [6], we consider only the effect of spin-polarized electrons. (It is simple to also include the net spin polarization of holes [7]). The resulting Zeeman splitting of the conduction band (Fig. 1a) is $2q\zeta = g\mu_B B$, where g is the g-factor for electrons, μ_B is Bohr magneton, q is the proton charge, and ζ is the electron magnetic potential [6].

Nonequilibrium electron and hole densities are n (the sum of spin up and spin down components $n_\uparrow + n_\downarrow$) and p, while the spin density and its polarization are $s = n_\uparrow - n_\downarrow$ and $\alpha = s/n$, respectively. Equilibrium values (with subscript "0") satisfy $n_0 p_0 = n_i^2 \cosh(\zeta/V_T)$ and $\alpha_0 = \tanh(\zeta/V_T)$, where n_i is the intrinsic (nonmagnetic) carrier density and $V_T = k_B T/q$, with k_B being the Boltzmann constant and T temperature. We assume [6] equilibrium values (ohmic contacts) for minority carriers at $x = -w_p, w_n$ and at $x = -w_p$ for spin density. To characterize the spin injection, at $x = w_n$ we impose $\delta s(w_n) = \alpha(w_n) N_d$, where $\delta s = s - s_0$ and $\delta\alpha = \alpha - \alpha_0$. (Neglecting $\delta p(w_n)$, which can accompany $\delta s(w_n)$, is an accurate approximation while $(w_n - d_n)$ is greater than the hole diffusion length [7].) In addition to spin injection by optical means [2] (depicted in Fig. 1b,e), an electrical spin injection (Fig. 1c,d) has been reported using a wide range of magnetic materials [10–15]. For a magnetic p-n junction total charge current J can be decomposed [6,7] as the sum of equilibrium-spin electron J_n and hole J_p currents, and spin-voltaic current J_{sv}, which originates from the interplay of the equilibrium magnetization (i.e. equilibrium spin polarization in the p region) and the nonequilibrium spin (injected in the n region).

The individual contributions of J as a function of applied bias V and B (recall that $\zeta = \zeta(B)$) are [6,7]

$$J_n = q\frac{D_n}{L_n} n_0(-d_p) \coth\left(\frac{\tilde{w}_p}{L_n}\right)\left(e^{V/V_T} - 1\right), \quad (1)$$

$$J_p = q\frac{D_p}{L_p} p_0(d_n) \coth\left(\frac{\tilde{w}_n}{L_p}\right)\left(e^{V/V_T} - 1\right), \quad (2)$$

$$J_{sv} = q\frac{D_n}{L_n} n_0(-d_p) \coth\left(\frac{\tilde{w}_p}{L_n}\right) e^{V/V_T} \alpha_0(-d_p)\delta\alpha(d_n), \quad (3)$$

where D_n (D_p) is the electron (hole) diffusivity, L_n and L_p are the minority diffusion lengths [16], and $\tilde{w}_p = w_p - d_p$ ($\tilde{w}_n = w_n - d_n$) is the width of the bulk p (n) region. There is an implicit V-dependence of $\tilde{w}_{n,p}$ since for the depletion layer edge [9] $d_{n,p} \propto \sqrt{V_b - V}$, where $V_b = V_T \ln(N_a N_d / n_i^2)$ is the built-in voltage. The derivation of the Eqs. 1-3 assumes that the depletion region is highly resistive (depleted from free carriers) [7,9]. The voltage drop between the two ends of the junction (see Fig. 1) and between $x = -w_p$ and $x = w_n$ can then be identified.

We next explore some properties of charge current which will be used to formulate the method for determining T_1. From Eq. 3 we note $J_{sv} \propto \delta\alpha(d_n)$, the spin-voltaic part of the charge current is related to the nonequilibrium spin. For a given injected spin, represented by $\delta\alpha(w_n)$, it follows (see Fig. 1a) that J_{sv} should be sensitive to: 1) $\tilde{w}_n$ the separation between the source of spin injection and the depletion layer edge, and 2) the spin diffusion length $L_{sn} = \sqrt{D_n T_1}$, characterizing the spin decay, i.e., $\delta\alpha(w_n)$. Indeed, one can show [6] that

$$\delta\alpha(d_n) = \delta\alpha(w_n)/\cosh(\tilde{w}_n/L_{sn}), \quad (4)$$

which from Eq. 3 implies a high sensitivity of J_{sv} to T_1 (through L_{sn}). In contrast, $J_{n,p}$ do not contain the nonequilibrium spin and thus have no T_1 dependence. A direct measurement of total charge current to identify T_1 [based on $J_{sv} = J_{sv}(T_1)$] implies some limitations. At vanishing bias ($V \ll V_T$), where $J_{n,p} \to 0$, $J \to J_{sv}$ is small, while at higher bias ($V \gg V_T$ and $V < V_b$) J is dominated by J_n and J_p–large T_1-independent background. To fully exploit simple I-V measurements we note that $T_1 = T_1(|B|)$ (the precise B-dependence differs for various spin-relaxation mechanisms). We also use the symmetry properties of the individual contributions to the charge current with respect to the applied magnetic field: $J_{n,p}(-B) = J_{n,p}(B)$, and $J_{sv}(-B) = -J_{sv}(B)$. This follows if we recall that $\zeta \propto B$, $J_n \propto \cosh(\zeta/V_T)$, J_p is ζ-independent, and $J_{sv} \propto \sinh(\zeta/V_T)$. Consequently, by measuring $J(V,B) - J(V,-B) = 2J_{sv}$ the large T_1-independent background has then been effectively removed. To optimize the experimental sensitivity we assume that, with the exception of T_1, all the material parameters are known and consider variable sample size which would give large difference in J_{sv} as T_1 is changed, i.e., large $\partial[\delta\alpha(d_n)]/\partial L_{sn}$ (see Eq. 4). For a given L_{sn} this is achieved with $\tilde{w}_n/L_{sn} \approx 1.5$ and to increase the magnitude of J_{sv} it is favorable to choose a short p region [17] ($J_{sv} \propto \coth(\tilde{w}_p/L_n)$) and to consider forward bias $V \gg V_T$, while still remaining in the low bias (low injection) regime ($V < V_b$). Since a priori we can only estimate a range of expected values for T_1 the choice of $\tilde{w}_n$ should maximize the corresponding values of $\partial[\delta\alpha(d_n)]/\partial L_{sn}$. The results obtained by this procedure are illustrated in Fig. 2.

The material parameters are based on GaAs [16] $D_n = 10D_p = 103.6$ cm^{2}s^{-1}, $L_n \approx 1.0$ μm, $L_p \approx 0.3$ μm, $n_i = 1.8 \times 10^6$ cm^{-3}. Doping with $N_a = N_d = 5 \times 10^{15}$ cm^{-3} at $V = 0$ yields $d_n = d_p \approx 0.4$ μm. For example, expecting that the spin relaxation time will be within 0.01 and 0.16 ns, to optimize sensitivity, we choose that for $T_1 = 0.16$ ns (which corresponds to $L_{sn} \approx 1.3$ μm) $\tilde{w}_n/L_{sn} \approx 1.5$. We set (at $V = 0$) $\tilde{w}_p \approx 0.3$ μm, which leads (see Fig. 1a,b) to $w_p = 0.7$ μm, $w_n = 2.3$ μm.

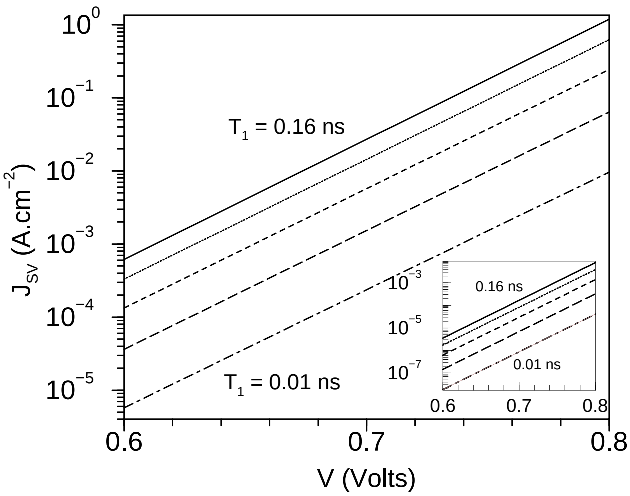

FIG. 2. Calculated spin-voltaic current J_{sv} for the magnetic *p-n* junction as a function of forward bias (in Volts). Lines (top to bottom) correspond to $T_1 = 0.16, 0.08, 0.04, 0.02$, and 0.01 ns, revealing the high sensitivity for probing the spin relaxation time. The doping is $N_a = N_d = 5 \times 10^{15}$ cm^{-3}. In the inset the results are displayed for $N_a = N_d = 5 \times 10^{17}$ cm^{-3} (all the other parameters remain unchanged), indicating that the high sensitivity to T_1 is preserved at different doping levels.

We use for the injected spin polarization $\delta\alpha(w_n) = 0.5$ and for the maximum spin splitting $2q\zeta/V_T = 0.2$, where at room temperature and B [Tesla] one can also write $q\zeta/V_T \approx 900B/g$ [6]. The sensitivity of our methods is displayed in Fig. 2 where for approximately an order of magnitude change in T_1 the spin-voltaic current J_{sv} changes by *two* orders of magnitude. Since the gist of the method outlined above relies on the robust symmetry properties of $J_{n,p}$ and J_{sv} with respect to B, it is straightforward to implement our proposal for a wide variety of magnetic *p-n* junctions where only a numerical solution is known. For example, higher (degenerate) doping could also be considered, typical for ferromagnetic semiconductors [8].

With the aid of the analytic solution of Eqs. 1-3 it is also possible to illustrate how to extract other quantities of interest. Consider the situation where we accurately know B and are interested in measuring g-factor in the magnetic p region. Recalling that $2q\zeta = g\mu_B B$, identifying ζ is then equivalent to extracting the g-factor. We use that $J_{n,p}$ is even in B and measure $J(V,B) + J(V,-B) = 2[J_n(V,B) + J_p(V,B)]$. From Eqs. 1 and 2 we note that the only dependence on ζ ($\propto B$) enters through $n_0(-d_p) = (n_i^2/N_a)\cosh(\zeta/V_T)$. Consequently, $J(V,B) + J(V,-B) \equiv a(V) + b(V)\cosh(\zeta/V_T)$, where functions a(V), b(V) are known and readily expressed in terms of the parameters from Eqs. 1 and 2. It remains then to measure $J(V,B) + J(V,-B)$ for different values of B and to obtain a one parameter fit for ζ, i.e., for the g-factor. (An attempt to extract ζ from J_{sv} would be more complicated, since it also contains, generally unknown, B-dependence in T_1.) If both ζ and T_1 are unknown, this procedure to obtain ζ should then be followed by measuring the spin-voltaic current to extract T_1, as discussed above. Finally, we consider the situation where ζ, T_1, and $\delta\alpha(w_n)$ are all unknown. Again we first extract ζ from $J(V,B) + J(V,-B)$ and subsequently the spin-voltaic current by measuring $J(V,B) - J(V,-B)$. It follows from Eq. 3 that the value of $\delta\alpha(d_n)$ can then be determined. However, $\delta\alpha(d_n)$ (see Eq. 4) still contains two unknown quantities: T_1 (L_{sn}) and $\delta\alpha(w_n)$ which influence needs to be decoupled. We assume (as it was implicitly done throughout the paper) that $\delta\alpha(w_n)$ is V-independent. We recall that change of applied bias modifies d_n. Effectively, we are changing the separation between the point of spin injection and spin "detection," since at the depletion edge $x = d_n$ the remaining nonequilibrium spin can be detected by its measurable effect on charge current. To eliminate influence of $\delta\alpha(w_n)$ we evaluate $f(V) = \delta\alpha[d_n(V_0)]/\delta\alpha[d_n(V)]$ for a range of applied bias and fixed V_0. In our case, it is suitable to choose $V \in [-0.8, 0.8]$ and $V_0 = -0.8$. Variation of $f(V)$ changes monotonically with T_1 and can be used to extract the spin relaxation time. However, the resulting sensitivity will be smaller that the one achieved in Fig. 2, under the assumption that T_1 is the only unknown quantity. [For $T_1 = 0.16$ ns $\Delta f(V) \equiv [f(0.8) - f(-0.8)]/f(-0.8) \approx 0.25$, while for $T_1 = 0.01$ ns $\Delta f(V) \approx 1.7$.] After T_1 is extracted we use then Eq. 4 to obtain $\delta\alpha(w_n)$, the only remaining unknown quantity.

We have proposed here how *all-electrical* measurements can be used to identify several quantities fundamental to the understanding of spin-polarized transport in semiconductors. The general principle that the nonequilibrium injected spin can produce measurable effects on charge current should be useful both for developing novel device concepts in semiconductor spintronics, as well as a diagnostic tool for the existing structures.

This work was supported by DARPA, NSF, and the US ONR.

[1] S. Das Sarma, J. Fabian, X. Hu, and I. Žutić, IEEE Transaction on Magnetics **36**, 2821 (2000); Superlattice Microst. **27**, 289 (2000); Solid State Commun. **119**, 207 (2001).

[2] F. Meier and B. P. Zakharchenya (eds), *Optical Orientation* (North-Holland, New York 1984).

[3] J. Fabian and S. Das Sarma, J. Vac. Sci. Technol. B **17**, 1780 (1999).

[4] R. H. Silsbee, Bull. Magn. Reson. **2**, 284 (1980).

[5] M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985).

[6] I. Žutić, J. Fabian, and S. Das Sarma, Phys. Rev. Lett. **88**, 066603 (2002).

[7] J. Fabian, I. Žutić, and S. Das Sarma, preprint.
[8] H. Ohno, Science **281**, 951 (1998).
[9] N. W. Ashcroft and N. D. Mermin, *Solid State Physics* (Saunders, New York, 1976).
[10] R. Fiederling, M. Kleim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag, and L. W. Molenkamp, Nature **402**, 787 (1999).
[11] Y. Ohno, D. K. Young, B. Beschoten, F. Matsukura, H. Ohno, and D. D. Awschalom, Nature **402**, 790 (1999).
[12] B. T. Jonker, Y. D. Park, B. R. Bennett, H. D. Cheong, G. Kioseoglou, and A. Petrou, Phys. Rev. B **62**, 8180 (2000).
[13] P. R. Hammar and M. Johnson, Appl. Phys. Lett. **79**, 2591 (2001).
[14] A. F. Isaković, D. M. Carr, J. Strand, B. D. Schultz, C. J. Palmstrøm, and P. A. Crowell, Phys. Rev. B **64**, 161304 (2001).
[15] A. T. Hanbicki, B. T. Jonker, G. Itskos, G. Kioseoglou, and A. Petrou, Appl. Phys. Lett. **80**, 1240 (2002).
[16] I. Žutić, J. Fabian, and S. Das Sarma, Phys. Rev. B **64**, 121201 (2001); Appl. Phys. Lett. **79**, 1558 (2001).
[17] $\tilde{w}_p > 0$, for ohmic boundary conditions to be accurate.